# Appendix A Detailed Model Description

This report describes the variables, constraints, and other attributes in the linear program formulation of ReEDS. It outlines, in order:

1. Subscripts (variables and constraints)
2. Major decision variables
3. The objective function
4. Constraints
5. Glossary of parameters

## A.1 Subscripts

Variables, parameters, and constraints are all subscripted to describe the space over which they apply. The various sets are listed below.

### A.1.1 Geographical Sets:

- *i, j*—356 supply/demand regions track where wind and solar power are generated and to where they are transmitted. Source regions are generally noted '*i*' and destinations, '*j*.'
- *n, p*—134 balancing authorities (abbreviated PCA, for Power Control Authority), each of which contains one or more supply/demand regions, track conventional generation. Source regions are generally noted '*n*' and destinations, '*p*.'
- *states*—There are 48 states (no Alaska or Hawaii).
- *rto*—32 regional transmission organizations, each of which contains one or more balancing authorities. Reserve margin requirements, operating reserve requirements, and wind curtailments are monitored at the RTO level.
- *r*—There are 13 nerc regions/subregions.
- *in*—There are 3 interconnects.

### A.1.2 Temporal Sets:

- *year*—2006 to 2050.
- *period*—There are 23 2-year periods.
- *s*—4 annual seasons.
- *m*—16 time-slices during each year, with four seasons and four daily time-slices in each season plus one superpeak time-slice. (Spring has only 3 slices.)

### A.1.3 Other Sets:

- *c*—5 wind classes.
- *l*—3 wind locations (*onshore, shallow offshore, deep offshore*).
- *wscp*—level of wind supply curve.
- *g*, *bp*—wind growth bracket and break points.

- *ginst*, *bpinst*—wind installations growth bracket and break points.
- *cCSP*—5 Concentrated Solar Power (CSP) classes.
- *cspscp*—level of csp supply curve.
- *gCSP*, *bpCSP*—CSP growth bracket and break points.
- *gCSPinst*, *bpCSPinst*—CSP installations growth bracket and break points.
- *escp*—level of intraregion electricity supply curve.
- *bioclass*—level of biomass supply curve.
- *geoclass*—level of geothermal resource supply curve.
- *egsclass*—level of conductive Enhanced Geothermal Systems (EGS) supply curve.
- *tpca_g*, *tpcabp*—transmission growth bracket and break points.
- *pol*—4 pollutants ($SO_2$, $NO_x$, $Hg$, $CO_2$).
- *q*—Conventional generating technologies:
  - hydropower
  - natural gas

    combustion turbine<br>combined cycle<br>combined cycle with carbon capture and sequestration (CCS)
  - coal

    traditional pulverized coal, unscrubbed, scrubbed, or cofiring<br>modern pulverized, with or without cofiring<br>integrated gasification combined cycle (IGCC) with or without CCS
  - oil-gas-steam
  - nuclear
  - dedicated biomass
  - geothermal
  - landfill gas/municipal solid waste
  - others (distributed PV).
- *st*—There are 4 storage technologies:
  - pumped hydropower (PHS)
  - batteries
  - compressed air energy storage (CAES).
  - ice-storage

## A.2 Major Decision Variables

The major decision variables include capacity of conventionals, renewables, and storage along with transmission; and dispatch of conventional capacity and storage. Unless otherwise noted, capacity variables are expressed in megawatts and energy variables are expressed in megawatt-hours.

Wind Variables

- $\mathrm{WturN}_{c,i,l,wscp}$ — new[3] wind capacity that will access pre-2006[4] transmission lines at a cost associated with step *wscp* of the transmission supply curve.[5]
- $\mathrm{WturTN}_{c,i,l}$ — New wind turbine capacity that can be transmitted only on new transmission lines dedicated to wind transmission from region $i$ to another region.
- $\mathrm{Wtur\_inregion}_{c,i,l}$ — New wind turbine capacity whose transmitted electricity will move on new transmission lines dedicated to wind from a class $c$ wind site within region $i$ to a load center also within region $i$.
- $\mathrm{WN}_{c,i,j,l}$ — Wind energy sent from new turbines in region $i$ to region $j$ that must be accomodated on pre-2006 lines.
- $\mathrm{WTN}_{c,i,j,l}$ — Wind energy sent from new turbines in region $i$ to region $j$ on new lines dedicated to wind.
- $\mathrm{Welec\_inregion}_{c,i,l,escp}$ Wind energy sent from new turbines in region $i$ to a load center also within region $i$.
- $\mathrm{WSurpLess}_{n,m}$ — The statistically calculated amount by which wind power supplied to balancing area $n$ exceeds the electricity demand in time-slice $m$
- $\mathrm{WCt}_{g}$ — New national wind turbine capacity in bin $g$; used for estimating the increase in wind turbine price with rapid world growth.
- $\mathrm{WCtinst}_{i,ginst}$ — New wind turbine capacity from bin *ginst* in region $i$; used for estimating the increase in installation costs with rapid regional growth.
- $\mathrm{WNSC}_{i,l,wscp}$ — New wind turbine capacity to be connected to the grid in region $i$ from step *wscp* of the supply curve, which provides the cost of building transmission from region $i$ to the grid.

CSP Variables

- $\mathrm{CSPturN}_{cCSP,i,cspscp}$ — new CSP capacity that will access pre-2006 transmission lines at a cost associated with step *cspscp* of the transmission supply curve.
- $\mathrm{CSPturTN}_{cCSP,i,j}$ — New CSP capacity that can be transmitted only on new transmission lines dedicated to CSP transmission from region $i$ to another region.
- $\mathrm{CSPtur\_inregion}_{cCSP,i}$ — New CSP capacity whose transmitted electricity will move on new transmission lines dedicated to CSP from a class *cCSP* site within region $i$ to a load center also within region $i$.
- $\mathrm{CSPN}_{cCSP,i,j}$ — CSP energy sent from new plants in region $i$ to region $j$ that must be accomodated on pre-2006 lines.

[3] New capacity means capacity built in this period, i.e. in this period's optimization run of the linear program.

[4] To reduce confusion, in the detailed model description, existing prior to the start of the model (2006) will be called "pre-2006" while existing prior to the start of a given period will be called "existing."

[5] in the model itself, WturN, WturTN, WN, and WTN are not actually subscripted with $c$. Instead, to reduce the solve time, a parameter $class_{c,i,l}$ keeps track of which class is the most attractive available in each region in that period. For this document, $class_{c,i,l}$ has been elided and $c$ has been integrated directly into the variables for simplicity.

- $\text{CSPTN}_{cCSP,i,j}$ — CSP energy sent from new plants in region $i$ to region $j$ on new lines dedicated to CSP.

- $\text{CSPelec\_inregion}_{cCSP,i,escp}$ — CSP energy sent from new plants in region $i$ to a load center also within region $i$.

- $\text{CSPCt}_{gCSP}$ — New national CSP capacity in bin *gCSP*; used for estimating the increase in CSP price with rapid world growth.

- $\text{CSPCtinst}_{i,gCSPinst}$ — New CSP capacity from bin *gCSPinst* in region $i$; used for estimating the increase in installation costs with rapid regional growth.

- $\text{CSPNSC}_{cspscp,i}$ — New CSP capacity to be connected to the grid in region $i$ from step *cspscp* of the supply curve, which provides the cost of building transmission from region $i$ to the grid.

- $\text{ReT}_{n,p}$ — New transmission capacity for wind or CSP (renewable) between balancing areas $n$ and $p$.

Conventional Variables

- $\text{CONV}_{n,q}$ — Dispatchable (primarily conventional) capacity of technology $q$ in balancing area $n$.[6]

- $\text{CONVgen}_{n,m,q}$ — Conventional generation in time-slice $m$ by technology $q$ in balancing area $n$.

- $\text{CONVP}_{n,m,q}$ — Peaking conventional generation in time-slice $m$ by technology $q$ in balancing area $n$.

- $\text{CCt}_{g,q}$ — Growth in conventional capacity per year.

- $\text{SR}_{n,m,q}$ — Spinning reserve capacity in time-slice $m$ by technology $q$ in balancing area $n$.

- $\text{QS}_{n,q}$ — Available quickstart capacity of technology $q$ in balancing area $n$.

- $\text{CONVT}_{n,p,m}$ — New transmission capacity for conventionals between balancing areas $n$ and $p$.

- $\text{GeoBin}_{geoclass,n}$ — New geothermal capacity by step on resource supply curve.

- $\text{GeoEGSBin}_{egsclass,n}$ — New EGS capacity by step on resource supply curve.

- $\text{BioBin}_{bioclass,n}$ — Biomass consumption by step on resource supply curve.

- $\text{BioGeneration}_{bioclass,n}$ — Generation from dedicated biomass plants by step on resource supply curve.

- $\text{CofireGen}_{bioclass,n}$ — Biomass-generated energy from coal-cofiring plants by step on resource supply curve.

Storage Variables

[6]Note that, for conventional capacity, the decision variable is not the new capacity, but the total capacity. This was done to simplify bookkeeping and to eliminate the need for vintaging of capacity built after 2006. To ensure that conventional capacity from previous periods (minus retirements) is built, a lower bound is specified for each of these variables. Thus the objective function value from the LP includes the full cost of all conventional capacity as well as the cost of their operation over the 20-year investment analysis period. This does not affect the amount of conventional capacity installed, because anything built beyond the lower bound must pay the marginal cost of new capacity. It does affect the amount of conventional fuel purchased, in that any capacity built in previous periods will have the same heatrate as the new capacity.

- $\mathrm{STOR}_{n,st}$ — Load-sited storage capacity of technology *st* in balancing area *n*.
- $\mathrm{STORin}_{n,m,st}$ — Energy used to charge load-sited storage in time-slice *m*.
- $\mathrm{STORout}_{n,m,st}$ — Energy discharged from load-sited storage in time-slice *m*.
- $\mathrm{STORor}_{n,m,st}$ — Operating reserve capacity of load-sited storage in time-slice *m*.

Miscellaneous Variables

- $\mathrm{TPCAN}_{n,p}$ — Transmission capacity between balancing areas *n* and *p*.
- $\mathrm{TPCACt}_{tpca\_g}$ — Growth in new transmission capacity per year.
- $\mathrm{CONTRACTcap}_{n,p}$ — Firm capacity contracted from balancing authority *n* to *p*.
- $\mathrm{COALLOWSUL}_{n,q}$ — Annual generation from low-sulfur coal by (coal-burning) technology *q*.
- RPS_shortfall — Unmet amount of RPS requirement. A penalty is assessed on the shortfalls in the objective function.
- $\mathrm{St\_RPS\_shortfall}_{states}$ — Unmet amount of state RPS requirement.
- $\mathrm{St\_CSPRPS\_shortfall}_{states}$ — Unmet amount of state CSP requirement.
- $\mathrm{Oper\_Res\_Reqt}_{rto,m}$ — Operating reserve capacity required in rto *rto*.

### A.3 Objective Function

In the objective function we minimize the following costs:

$$
\begin{aligned}
z \quad = \quad & \text{Capital and operating costs of new wind plants} \\
+ \quad & \text{Cost of new transmission for wind} \\
+ \quad & \text{Capital and operating costs of new CSP plants} \\
+ \quad & \text{Cost of new transmission for CSP} \\
+ \quad & \text{Capital cost of conventional generators} \\
+ \quad & \text{Fuel and operating costs of conventional generation} \\
+ \quad & \text{Capital cost of new transmission lines} \\
+ \quad & \text{Capital cost of new storage capacity} \\
+ \quad & \text{Fuel and operating costs of storage} \\
+ \quad & \text{Cost of a } CO_2 \text{ tax}
\end{aligned}
$$

In equation form, with explanatory notes in brackets (below the lines to which they refer):[7] [8]

$$
\begin{aligned}
z \quad = \quad & \sum_{c,i,l} (\mathrm{WturN}_{c,i,l} + \mathrm{WturTN}_{c,i,l} + \mathrm{Wtur\_inregion}_{c,i,l}) \\
& \cdot \begin{pmatrix} CW_c \cdot cpop_{c,i,l} \cdot (1 + cslope_{c,i,l} \cdot Cost\_Inst\_Frac) \\ \cdot (1 - st\_Invincent_{i \in states}) \\ + CWOM_c + CF_{c,l} \cdot (1 - st\_Prodincent_{i \in states}) \end{pmatrix} \\
& \qquad \text{[wind capital and O\&M costs]} \\
+ \quad & \sum_{c,i,l} \left( \sum_{j} \left( \mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l} \right) + \mathrm{Welec\_inregion}_{c,i,l} \right) \cdot GridConCost \\
& \qquad \text{[wind capital and O\&M costs]} \\
+ \quad & \sum_{c,i,j,l} \mathrm{WN}_{c,i,j,l} \cdot CF_{c,l} \cdot (TOWCOST \cdot Distance_{i,j} + PostStamp_{i,j}) \\
& \cdot (1 - SurplusMar_{c,i}) \cdot 8760/CRF \\
& \qquad \text{[cost to connect wind to grid on pre-2006 lines]} \\
+ \quad & \sum_{c,i,l} \mathrm{WTN}_{c,i,j,l} \cdot TNWCOST \cdot Distance_{i,j} \\
& \qquad \text{[cost to connect wind to grid on new lines]} \\
+ \quad & \sum_{g} \mathrm{WCt}_g \cdot CG_g \\
& \qquad \text{[excessive growth penalty on wind turbines]} \\
+ \quad & \sum_{ginst,i} \mathrm{WCtinst}_{ginst,i} \cdot CGinst_{ginst} \\
& \qquad \text{[excessive growth penalty on wind installation]}
\end{aligned}
$$

[7] some subscripts, e.g. *wscp* on WturN in the first line of the objective function are elided here and in constraints, below, when they are immediately summed over and therefore have no bearing on the equation.

[8] All parameters used in the objective function and constraints can be found in the glossary, below.

$$+ \quad \sum_{c,i,l} \left( \sum_{wscp} \mathrm{WNSC}_{i,l,wscp} \cdot WR2GPTS_{c,i,l,wscp} \right) \cdot CF_{c,l} \cdot 8760/CRF$$

[cost of spur line to connect new wind capacity to pre-2006 grid]

$$+ \quad \sum_{c,j,l} \left( \sum_{escp} \mathrm{Welec\_inregion}_{c,j,l,escp} \cdot MW\_inregion\_dis_{c,j,escp} \right) \cdot CF_{c,l} \cdot 8760/CRF$$

[cost of spur line to connect new wind capacity to inregion load]

$$+ \quad \sum_{cCSP,i} \left( \mathrm{CSPturN}_{cCSP,i} + \mathrm{CSPturTN}_{cCSP,i} + \mathrm{CSPtur\_inregion}_{cCSP,i} \right) \cdot (CCSP_{cCSP} + CSPOM_{cCSP})$$

[CSP capital and O&M costs]

$$+ \quad \sum_{cCSP,i,j} \left( \mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j} + \mathrm{CSPelec\_inregion}_{cCSP,i,j} \right) \cdot CSPGridConCost$$

[inregion CSP capital and O&M costs]

$$+ \quad \sum_{cCSP,i,j,m} \mathrm{CSPN}_{cCSP,i,j} \cdot H_m \cdot CF_{cCSP,m} \cdot (TOWCOST \cdot Distance_{i,j} + PostStamp_{i,j}) \cdot (1 - CSPSurplusMar_{cCSP,i})/CRF$$

[cost to connect CSP to grid on pre-2006 lines]

$$+ \quad \sum_{cCSP,i,j} \mathrm{CspTN}_{cCSP,i,j} \cdot TNWCOST \cdot Distance_{i,j}$$

[cost to connect CSP to grid on new lines]

$$+ \quad \sum_{cCSP,i,j,m} \left( \sum_{cspscp} \mathrm{CspNSC}_{cCSP,i,cspscp} \cdot CSP2GPTS_{cCSP,i,cspscp} \right) \cdot CF_{cCSP,m} \cdot H_m/CRF$$

[cost of spur line to connect new wind capacity to pre-2006 grid]

$$+ \quad \sum_{cCSP,i,j,m} \left( \sum_{escp} \mathrm{CspELEC\_inregion}_{cCSP,j,escp} \cdot CSP\_inregion\_dis_{cCSP,j,escp} \right) \cdot \frac{CF_{cCSP,m} \cdot H_m}{CRF}$$

[cost of spur line to connect new CSP capacity to inregion load]

$$+ \quad \sum_{gCSP} \mathrm{CSPCt}_{gCSP} \cdot CGcsp_{gCSP}$$

[excessive growth penalty on CSP hardware]

$$+ \quad \sum_{gCSPinst,i} \mathrm{CSPCtinst}_{gCSPinst,i} \cdot CGcspinst_{gCSPinst}$$

[excessive growth penalty on CSP installation]

$$+ \quad \sum_{n,q} \mathrm{CONV}_{n,q} \cdot (CCONV_q + CCONVF_q + Ctranadder_q + GridConCost)$$

[capital and O&M costs for conventional generators]

$$+ \quad \sum_{n,p} \mathrm{CONVT}_{n,p,m} \cdot H_m/CRF \cdot \left( TOCOST \cdot Distance_{n,p} + PostStamp_{n,p} \right)$$

[variable costs for transmission]

$$+ \quad \sum_{q,g} \mathrm{CGconv}_{q,g} \cdot CCt_{q,g}$$

[excessive growth penalty on conventional capacity]

$$+ \sum_{n,p} \mathrm{TPCAN}_{n,p} \cdot \mathit{TNCOST} \cdot \mathit{Distance}_{n,p}$$

[capital cost of new transmission lines]

$$+ \sum_{TPCA\_G} \mathrm{TPCA\_CG}_{TPCA\_G} \cdot \mathrm{TPCA\_Ct}_{TPCA\_G}$$

[excessive growth penalty on new transmission]

$$+ \sum_{n,m,q} \mathrm{CONVgen}_{n,m,q} \cdot H_m \cdot \mathit{CCONVV}_{n,q}$$

[operating and fuel costs for conventional generators]

$$+ \sum_{n,m,q} \mathrm{CONVP}_{n,m,q} \cdot H_m \cdot \mathit{CCONVV}_{n,q} \cdot \mathit{PcostFrac}_q$$

[increased operating cost for peaking power]

$$+ \sum_{n,m,q} \mathrm{SR}_{n,m,q} \cdot H_m \cdot \mathit{CSRV}_{n,q}$$

[operating and fuel costs for spinning reserve]

$$+ \sum_{n,q} \mathrm{QS}_{n,q} \cdot \mathit{CQS}$$

[cost for quickstart capacity]

$$+ \sum_{geoclass,n} \mathrm{GeoBin}_{geoclass,n} \cdot \mathit{GeoAdder}_{geoclass,n} \cdot \mathit{CCONV}_{geothermal} / \mathit{CCC}_{geothermal}$$

$$+ \sum_{egsclass,n} \mathrm{GeoEGSBin}_{egsclass,n} \cdot \mathit{GeoAdder}_{egsclass,n} \cdot \mathit{CCONV}_{geothermal} / \mathit{CCC}_{geothermal}$$

[supply curve-based cost for geothermal capacity]

$$+ \sum_{bioclass,n} \mathrm{BioGeneration}_{bioclass,n} \cdot \mathit{CHeatRate}_{biopower} \cdot \mathit{BioFeedstockLCOF}_{bioclass,n}$$

$$+ \sum_{bioclass,n} \mathrm{CofireGen}_{bioclass,n} \cdot \mathit{CHeatRate}_{cofire} \cdot (\mathit{BioFeedstockLCOF}_{bioclass,n} - \mathit{Fprice}_{coal,n})$$

[supply curve-based cost for biomass feedstock]

$$+ \sum_{st,n} \mathrm{STOR}_{st,n} \cdot (\mathit{CSTOR}_{st} + \mathit{FSTOR}_{st} / \mathit{CRF})$$

[capital and O&M costs for storage]

$$+ \sum_{n,m,st} \mathrm{STORin}_{n,m,st} \cdot H_m$$

$$\cdot (\mathit{VSTOR}_{st} \cdot \mathit{STOR\_RTE}_{st} + \mathit{Fprice}_{CAES,n} \cdot \mathit{CAESHeatRate})$$

[operating and fuel costs for storage]

$$+ \sum_{st,storagebp} \mathrm{STORAGEBIN}_{st,storagebp} \cdot \mathit{CGStorage}_{st,storagebp}$$

[excessive growth penalty on new storage]

$$+ \sum_{n,m,q} (\mathrm{CONVgen}_{n,m,q} + \mathrm{CONVP}_q) \cdot H_m \cdot \mathit{CONVpol}_{q,CO2} \cdot \mathit{CHeatRate}_q \cdot \mathit{CarbTax}$$

[cost of carbon tax on conventional generation]

$$+ \sum_{n,m,st} \mathrm{STORout}_{n,m,st} \cdot H_m \cdot \mathit{STORpol}_{st,CO2} \cdot \mathit{CHeatRate}_{st} \cdot \mathit{CarbTax}$$

[cost of carbon tax on storage generation]

$$+ \quad \sum_{n,q} \mathrm{COALLOWSUL}_{n,q} \cdot \mathit{lowsuladd\_LCF}_n \cdot \mathit{CHeatRate}_q$$

[surcharge for using low sulfur coal]

$$+ \quad \mathrm{RPS\_shortfall} \cdot \mathit{RPSSCost}$$

$$+ \quad \sum_{states} \mathrm{St\_RPSshortfall}_{states} \cdot \mathit{St\_RPSSCost}$$

$$+ \quad \sum_{states} \mathrm{St\_CSPRPSshortfall}_{states} \cdot \mathit{St\_CSPRPSCost}_{states}$$

[costs of shortfalls in failing to meet RPS requirements]

## A.4 Constraints

The minimization of cost in ReEDS is subject to a large number of different constraints, involving limits on resources, transmission constraints, national growth constraints, ancillary services, and pollution. Unless specifically noted otherwise (see, for example, the wind resource limit below), these constraints apply to new generating capacity built in the time period being optimized.

The constraint name is shown with the subscripts over which the constraint applies. For example, in the constraint immediately below, the subscript '$c, i, l$' immediately following the name of the constraint implies that this constraint is applied for every class of wind $c$, every region $i$, and every location $l$. Because there are 356 regions, five classes of wind, and 3 locations, this first type of constraint is repeated 5,340 times (356x5x3).

### A.4.1 Constraints on Wind

**Wind Resource Constraint:** For every wind class $c$ and wind supply region $i$, the sum of all wind capacity installed in this and preceding time periods must be less than the total wind resource in the region.

$\mathit{WIND\_RES\_UC}_{c,i,l}$

$$\mathrm{WturN}_{c,i,l} + \mathrm{WturTN}_{c,i,l} + \mathrm{Wtur\_inregion}_{c,i,l} \quad \leq \quad \max(0, \mathit{WRuc}_{c,i,l} - \mathit{WturO}_{c,i,l} - \mathit{WTturO}_{c,i,l})$$

**Wind Supply Curve:** New wind of class $c$ in region $i$ at interconnection cost step $wscp$ must be less than the remaining wind resource in that cost step.[9] The second constraint balances the wind on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

$\mathit{WIND\_supply\_curves}_{c,i,l,wscp}$

$$\mathrm{WturN}_{c,i,l,wscp} \quad \leq \quad \max(0, \mathit{WR2G}_{c,i,l,wscp})$$

$\mathit{WIND\_EXISTRANS\_BALANCE}_{i,l}$

$$\sum_{wscp} \mathrm{WNSC}_{i,l,wscp} \quad = \quad \sum_{j} \mathrm{WN}_{i,j,l}$$

[9]A preliminary optimization is performed outside and prior to the main model to construct a supply curve for onshore wind, shallow offshore wind, and deep offshore wind for each wind class $c$ and region $i$. This supply curve is comprised of four quantity/cost pairs ($\mathit{WR2G}_{c,i,l,wscp}$ / $\mathit{WR2GPTS}_{c,i,l,wscp}$ ). The "curve" provides the amount of class $c$ wind $\mathit{WR2G}_{c,i,l,wscp}$ that can be connected to the pre-2006 grid for a cost between $\mathit{WR2GPTS}_{c,i,l,wscp-1}$ and $\mathit{WR2GPTS}_{c,i,l,wscp}$. This "pre-LP" optimization is described in more detail in Appendix G. The quantity $\mathit{WR2G}_{c,i,l,wscp}$ is reduced after each period's LP optimization by the amount of wind used in the time period from that cost step.

**Wind Transmission Constraint:** The new class $c$ wind transmitted from a region $i$ to all regions $j$ must be less than or equal to the total amount of new region $i$ class $c$ wind used from the class $c$ wind supply curve.

$WIND\_2\_GRID_{c,i,l}$

$$\sum_{j} \mathrm{WN}_{c,i,j,l} \leq \sum_{wscp} \mathrm{WturN}_{c,i,l,wscp}$$

$WIND\_2\_NEW_{c,i,l}$

$$\sum_{j} \mathrm{WTN}_{c,i,j,l} \leq \sum_{wscp} \mathrm{WturTN}_{c,i,l,wscp}$$

$WIND\_INREGION_{c,i,l}$

$$\sum_{escp} \mathrm{Welec\_inregion}_{c,i,l,escp} \leq \mathrm{Wtur\_inregion}_{c,i,l}$$

**Wind Growth Constraint:** These two constraints allocate new wind capacity (MW) to bins that have turbine prices that are higher than the costs during periods of rapidly growing demand. The bins are defined as a fraction of the national wind capacity (MW) at the start of the period.

$WIND\_GROWTH\_TOT$

$$\sum_{c,i,l} (\mathrm{WturN}_{c,i,l} + \mathrm{WturTN}_{c,i,l} + \mathrm{Wtur\_inregion}_{c,i,l}) \leq \sum_{g} \mathrm{WCt}_{g}$$

$WIND\_GROWTH\_BIN_{g}$

$$\mathrm{WCt}_{g} \leq Gt_{g} \cdot BASE\_WIND$$

**Wind Installation Growth Constraint:** These two constraints allocate new wind capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional wind capacity (MW) at the start of the period.

$WIND\_GROWTH\_INST_{i}$

$$\sum_{c,l} (\mathrm{WturN}_{c,i,l} + \mathrm{WturTN}_{c,i,l} + \mathrm{Wtur\_inregion}_{c,i,l}) - 200 \leq \sum_{ginst} \mathrm{WCtinst}_{i,ginst}$$

$WIND\_GROWTH\_BIN\_INST_{i,ginst}$

$$\mathrm{WCtinst}_{i,ginst} \leq Gtinst_{ginst} \cdot BASE\_WIND\_inst_{i}$$

**Wind Curtailments:** This constraint defines wind curtailments based on a statistical approach. SurplusOld and SurplusMar are calculated in between investment periods based on a statistical approach and as described in Appendix D. The last term on the right hand side reduces the amount of curtailed wind power if new storage is built in balancing area $n$. $\mathrm{WSurpLess}_{n,m}$ is then subtracted from the wind contribution to meeting the *LOAD_PCA* constraint for time-slice $m$ and for the RPS requirement.

*WIND_RECOVERY$_{n,m}$*

$$
\begin{aligned}
\text{WSurpLess}_{n,m} \quad \geq \quad & \text{SurplusOld}_{n,m} \\
+ \quad & \sum_{c,i,j,l}^{j \in n} (\text{WN}_{c,i,j,l} + \text{WTN}_{c,i,j,l} + \text{Welec\_inregion}_{c,j,l}) \cdot (1 - \mathit{TWLOSSnew} \cdot \mathit{Distance}_{i,j}) \cdot \text{SurplusMar}_{n,m} \\
- \quad & \sum_{st} \mathit{SurplusRecoveryPerStorage}_{n,m} \cdot \text{STOR}_{n,st}
\end{aligned}
$$

### A.4.2 Constraints on CSP

**CSP Resource Limit:** For every CSP class and supply region $i$, the sum of all CSP capacity installed in this and preceding time periods must be less than the total solar resource in the region.

*CSP_REC_UC$_{cCSP,i}$*

$$
\begin{aligned}
&\text{CSPturN}_{cCSP,i} + \text{CSPturTN}_{cCSP,i} \quad + \\
&\qquad \text{CSPtur\_inregion}_{cCSP,i} \quad \leq \quad \max(0, \mathit{CSPRuc}_{cCSP,i} - \mathit{CSPturO}_{cCSP,i} - \mathit{CSPTturO}_{cCSP,i})
\end{aligned}
$$

**CSP Supply Curve:** New CSP of class cCSP in region $i$ at interconnection cost step *cspscp* must be less than the remaining solar resource in that cost step. The second constraint balances the CSP on pre-2006 lines across the different supply curve points and is used to determine the cost of transmission required to reach the grid.

*CSP_supply_curves$_{cCSP,i,cspscp}$*

$$\text{CSPturN}_{cCSP,i,cspscp} \quad \leq \quad \max(0, \mathit{CSP2G}_{cCSP,i,cspscp})$$

*CSP_EXISTRANS_BALANCE$_i$*

$$\sum_{cspscp} \text{CspNSC}_{i,cspscp} \quad = \quad \sum_{j} \text{CspN}_{i,j}$$

**CSP Transmission Constraints:** New CSP transmitted from a region $i$ to all regions $j$ must be less than or equal to the total amount of new region $i$ CSP used from the solar supply curve.

*CSP_2_GRID$_{cCSP,i}$*

$$\sum_{j} \text{CSPN}_{cCSP,i,j} \quad \leq \quad \sum_{cspscp} \text{CSPturN}_{cCSP,i,cspscp}$$

*CSP_2_NEW$_{cCSP,i}$*

$$\sum_{j} \text{CSPTN}_{cCSP,i,j} \quad \leq \quad \sum_{cspscp} \text{CSPturTN}_{cCSP,i,cspscp}$$

*ELEC_inregioncsp$_{cCSP,i}$*

$$\sum_{escp} \text{CSPELEC\_inregion}_{cCSP,i,escp} \quad \leq \quad \text{CSPtur\_inregion}_{cCSP,i}$$

**CSP Growth Constraint:** These two constraints allocate new CSP capacity (MW) to bins that have plant costs associated with them over and above the costs of the solar plants themselves. The bins are defined as a fraction of the national CSP capacity (MW) at the start of the period.

*CSP_GROWTH_TOT*

$$\sum_{cCSP,i} (\text{CSPturN}_{cCSP,i} + \text{CSPturTN}_{cCSP,i} + \text{CSPtur\_inregion}_{cCSP,i}) \quad \leq \quad \sum_{gCSP} \text{CSPCt}_{gCSP}$$

*CSP_GROWTH_BIN*$_{gCSP}$

$$\text{CSPCt}_{gCSP} \quad \leq \quad GtCSP_{gCSP} \cdot BASE\_CSP$$

**CSP Installation Growth Constraint:** These two constraints allocate new CSP capacity (MW) to bins that have installation costs associated with them over and above the base costs of installation. The bins are defined as a fraction of the regional CSP capacity (MW) at the start of the period.

*CSP_GROWTH_INST*$_i$

$$\sum_{cCSP} (\text{CSPturN}_{cCSP,i} + \text{CSPturTN}_{cCSP,i} + \text{CSPtur\_inregion}_{cCSP,i}) - 200 \quad \leq \quad \sum_{gCSPinst} \text{CSPCtinst}_{i,gCSPinst}$$

*CSP_GROWTH_BIN_INST*$_{i,gCSPinst}$

$$\text{CSPCtinst}_{i,gCSPinst} \quad \leq \quad GtCSPinst_{gCSPinst} \cdot BASE\_CSP\_inst_i$$

### A.4.3 General Renewable Constraints

**State RPS Requirement:** This allows the model to include state Renewable Portfolio Standards (RPS), wherein the total annual renewable generation must exceed a specified fraction of the state electricity load or a penalty must be paid on the shortfall.

*ST_RPSConstraint*$_{states}$

$$
\begin{aligned}
St\_RPSfraction_{states} \cdot \sum_{n,m}^{n \in states} L_{n,m} \cdot H_m \quad \leq \quad & \sum_{c,i,j,m,l}^{j \in states} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
& \quad \cdot (1 - TWLOSSnew \cdot Distance_{i,j})(1 - SurplusMar_{c,j}) \\
+ & \sum_{c,i,j,m}^{j \in states} (WO_{c,i,j,l} + WTO_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
& \quad \cdot (1 - TWLOSSold \cdot Distance_{i,j})(1 - SurplusOld_{c,j}) \\
+ & \sum_{c,j,m}^{j \in states} \mathrm{Welec\_inregion}_{c,j,l} \cdot CF_{c,j,m,l} \cdot H_m \\
& \quad \cdot (1 - SurplusMar_{c,j}) \\
+ & \sum_{cCSP,i,j,m}^{j \in states} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
& \quad \cdot (1 - TWLOSSnew \cdot Distance_{i,j}) \\
+ & \sum_{cCSP,i,j,m}^{j \in states} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
& \quad \cdot (1 - TWLOSSold \cdot Distance_{i,j}) \\
+ & \sum_{cCSP,j,m}^{j \in states} \mathrm{CSPelec\_inregion}_{cCSP,j} \cdot CF_{cCSP,m} \cdot H_m \\
+ & \sum_{c,i,m,st}^{j \in states} (\mathrm{WSTORin\_wind}_{c,i,m,st} + old\_WSTORin\_wind_{c,i,m,st}) \cdot H_m \\
+ & \sum_{n,m}^{n \in states} (\mathrm{CONV}_{n,m,geothermal} + \mathrm{CONVP}_{n,m,geothermal}) \cdot H_m \\
+ & \sum_{n,m}^{n \in states} (\mathrm{CONV}_{n,m,biopower} + \mathrm{CONVP}_{n,m,biopower}) \cdot H_m \\
+ & \sum_{bioclass,n} \mathrm{CofireGen}_{bioclass,n} \\
- & \sum_{n,m}^{n \in states} \mathrm{WSurpLess}_{n,m} \cdot H_m \\
+ & \ \mathrm{St\_RPS\_Shortfall}
\end{aligned}
$$

**RPS Requirement:** This allows the model to include a national Renewable Portfolio Standard.

*RPSConstraint*

$$
\begin{aligned}
&\mathit{RPSfraction}\cdot \\
&\Big( \sum_{c,i,j,m,l} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&+ \sum_{c,i,j,m,l} (WO_{c,i,j,l} + WTO_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&+ \sum_{c,j,m,l} \mathrm{Welec\_inregion}_{c,j,l} \cdot CF_{c,j,m,l} \cdot H_m \\
&+ \sum_{cCSP,i,j,m} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{cCSP,i,j,m} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{cCSP,j,m} \mathrm{CSPelec\_inregion}_{cCSP,j} \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{n,m,q} (\mathrm{CONV}_{n,m,q} + \mathrm{CONVP}_{n,m,q}) \cdot H_m \\
&+ \sum_{n,m} (\mathrm{STORout}_{n,m,CAES} - \mathrm{STORin}_{n,m,CAES}) \cdot H_m \\
&- \sum_{n,m} \mathrm{WSurpLess}_{n,m} \cdot H_m \Big) \\
&\leq \sum_{c,i,j,m,l} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&+ \sum_{c,i,j,m,l} (WO_{c,i,j,l} + WTO_{c,i,j,l}) \cdot CF_{c,i,m,l} \cdot H_m \\
&+ \sum_{c,j,m,l} \mathrm{Welec\_inregion}_{c,j,l} \cdot CF_{c,j,m,l} \cdot H_m \\
&+ \sum_{cCSP,i,j,m} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{cCSP,i,j,m} (CSPO_{cCSP,i,j} + CSPTO_{cCSP,i,j}) \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{cCSP,j,m} \mathrm{CSPelec\_inregion}_{cCSP,j} \cdot CF_{cCSP,m} \cdot H_m \\
&+ \sum_{n,m} (\mathrm{CONV}_{n,m,hydro} + \mathrm{CONV}_{n,m,lfill} + \mathrm{CONV}_{n,m,distPV}) \cdot H_m \\
&+ \sum_{n,m} (\mathrm{CONV}_{n,m,geothermal} + \mathrm{CONVP}_{n,m,geothermal}) \cdot H_m \\
&+ \sum_{n,m} (\mathrm{CONV}_{n,m,biopower} + \mathrm{CONVP}_{n,m,biopower}) \cdot H_m \\
&+ \sum_{bioclass,n} \mathrm{CofireGen}_{bioclass,n} \\
&- \sum_{n,m} \mathrm{WSurpLess}_{n,m} \cdot H_m \\
&+ \mathrm{RPS\_Shortfall}
\end{aligned}
$$

**Limits on Existing Transmission:** Due to extant transmission capacity usage and other limitations, the amount of wind power able to be transported on pre-2006 lines is limited. This constraint limits the wind imports on pre-2006 lines to some fraction of the capacity of the transmission lines crossing the boundaries of demand region $j$.

*WIND_interregion_trans$_j$*

$$\begin{aligned} \sum_{c,i,l} (\mathrm{WN}_{c,i,j,l} + WO_{c,i,j,l}) - \sum_{c,l} (\mathrm{WN}_{c,j,j,l} + WO_{c,j,j,l}) \quad + \\ \sum_{cCSP,i} (\mathrm{CspN}_{cCSP,i,j} + CspO_{cCSP,i,j}) - \sum_{cCSP} (\mathrm{CspN}_{cCSP,j,j} + CspO_{cCSP,j,j}) \quad \leq \quad \sum_{k} a_k \cdot Tk_k \end{aligned}$$

**Regional Balancing Constraint:** This constraint is a transmission capacity balance that defines the transmission capacity needed to handle wind and CSP transmission between balancing authorities. This transmission capacity required for wind/CSP is combined with that required by conventional generation to identify bottlenecks between balancing authorities. The left-hand side of the constraint is the sum of all wind and CSP generation transmitted into the balancing authority plus all that generated within. The right-hand side is the sum of all the wind and CSP generation consumed in- plus all that transmitted from the balancing authority.

*WIND_BALANCE_PCAS$_n$*

$$\begin{aligned} \sum_{p} \mathrm{ReT}_{n,p} \quad + & \\ \sum_{c,i,j,l}^{i \in n} (\mathrm{WN}_{c,i,j,l} + WO_{c,i,j,l}) \quad + & \\ \sum_{cCSP,i,j}^{i \in n} (\mathrm{CSPN}_{cCSP,i,j} + CspO_{cCSP,i,j}) \quad = & \quad \sum_{p} \mathrm{ReT}_{p,n} \\ & + \sum_{c,i,j,l}^{j \in n} (\mathrm{WN}_{c,i,j,l} + WO_{c,i,j,l}) \\ & + \sum_{cCSP,i,j}^{j \in n} (\mathrm{CSPN}_{cCSP,i,j} + CspO_{cCSP,i,j}) \end{aligned}$$

**Conventional Transmission Constraint:** Ensures that there is sufficient transmission capacity between contiguous balancing authorities $n$ and $p$ within the same grid interconnect to transmit wind generation and conventional generation in each time-slice $m$. Transmission capacity added this period is included in both directions $p$-to-$n$ and $n$-to-$p$ because transmission lines are bidirectional.[10]

*CONV_TRAN_PCA$_{n,p,m}$*

$$\mathrm{CONVT}_{n,p,m} + \mathrm{ReT}_{n,p} \quad \leq \quad \mathrm{TPCAN}_{n,p} + \mathrm{TPCAN}_{p,n} + TPCAO_{n,p}$$

[10]The $\mathrm{ReT}_{n,p}$ variable prevents ReEDS from shipping wind or CSP from supply region $i$ to the closest demand region $j$; and, from there, continue to ship it as conventional power to other balancing authorities where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different balancing authority, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.

**Contracted Transmission Constraint:** Ensures that there is sufficient transmission capacity between contiguous balancing authorities $n$ and $p$ within the same grid interconnect to transmit wind generation and contracted conventional capacity. Transmission capacity added this period is included in both directions $p$-to-$n$ and $n$-to-$p$ because transmission lines are bidirectional.

*CONTRACT_TRAN_PCA*$_{n,p}$

$$\mathrm{CONTRACTcap}_{n,p} + \mathrm{WT}_{n,p} + \mathrm{CspT}_{n,p} \quad \leq \quad \mathrm{TPCAN}_{n,p} + \mathrm{TPCAN}_{p,n} + TPCAO_{n,p}$$

**Transmission Growth Constraints:** These two constraints allocate new transmission capacity (MW) to bins that have costs associated with them over and above the cost of the transmission lines themselves. The bins are defined as a fraction of the national transmission capacity at the start of the period.

*TPCA_GROWTH_TOT*

$$\mathrm{TPCAN}_{n,p} + \sum_{c,i,j} \mathrm{WTN}_{c,i,j} + \sum_{cCSP,i,j} \mathrm{CspTN}_{cCSP,i,j} \quad \leq \quad \sum_{TPCA\_g} \mathrm{TPCA\_Ct}_{TPCA\_g}$$

*TPCA_GROWTH_BIN*$_{TPCA\_g}$

$$\mathrm{TPCA\_Ct}_{TPCA\_g} \quad \leq \quad TPCA\_Gt_{TPCA\_g} \cdot BASETPCA$$

### A.4.4 Constraints on System Operation

**Generation Requirement:** This constraint ensures that the load (MW) in time period $m$ in balancing authority $n$ is met with power from conventional and renewable generators plus net imports from balancing authorities contiguous to $n$ ($\mathrm{CONVT}_{n,p,m}$). Long-distance transmission from wind and CSP facilities and imports are decremented for transmission losses. Wind and CSP output are also decreased by wind curtailments. Storage can also contribute, but the charging of storage adds to the load requirement.
The *LOAD_PCA* constraint is the constraint that is affected by the mini-slices; for $(n, m)$ pairs that qualify, it is split into three independent constraints (each with a different set of wind capacity factors) that must be dispatched separately.

*LOAD_PCA*$_{n,m}$

$$
\begin{aligned}
L_{n,m} \quad \leq \quad & \sum_{q} (\mathrm{CONVgen}_{n,m,q} + \mathrm{CONVP}_{n,m,q}) \\
+ \quad & \sum_{p} (\mathrm{CONVT}_{p,n,m} \cdot (1 - \mathit{TWLOSS} \cdot \mathit{Distance}_{n,p}) - \mathrm{CONVT}_{n,p,m}) \\
+ \quad & \sum_{c,i,j}^{j \in n} (\mathrm{WN}_{c,i,j,l} + \mathrm{WTN}_{c,i,j,l}) \cdot \mathit{CF}_{c,i,m,l} \cdot (1 - \mathit{TWLOSSnew} \cdot \mathit{Distance}_{i,j}) \\
+ \quad & \sum_{c,j,l}^{j \in n} \mathrm{Welec\_inregion}_{c,j,l} \cdot \mathit{CF}_{c,j,m,l} \\
+ \quad & \sum_{c,i,j,l}^{j \in n} (\mathit{WO}_{c,i,j,l} + \mathit{WTO}_{c,i,j,l}) \cdot \mathit{CFO}_{c,i,m,l} \cdot (1 - \mathit{TWLOSSold} \cdot \mathit{Distance}_{i,j}) \\
- \quad & \mathrm{WSurpLess}_{n,m} \\
+ \quad & \sum_{cCSP,i,j}^{j \in n} (\mathrm{CSPN}_{cCSP,i,j} + \mathrm{CSPTN}_{cCSP,i,j}) \cdot \mathit{CF}_{cCSP,m} \cdot (1 - \mathit{TWLOSSnew} \cdot \mathit{Distance}_{i,j}) \\
+ \quad & \sum_{cCSP,j}^{j \in n} \mathrm{CSPelec\_inregion}_{cCSP,j} \cdot \mathit{CF}_{cCSP,m} \\
+ \quad & \sum_{cCSP,i,j}^{j \in n} (\mathit{CSPO}_{cCSP,i,j} + \mathit{CSPTO}_{cCSP,i,j}) \cdot \mathit{CF}_{cCSP,m} \cdot (1 - \mathit{TWLOSSold} \cdot \mathit{Distance}_{i,j}) \\
+ \quad & \sum_{st} (\mathrm{STORout}_{n,m,st} - \mathrm{STORin}_{n,m,st})
\end{aligned}
$$

**Reserve Margin Requirement:** Ensures that the conventional and storage capacity (MW) and capacity value of wind and CSP during the peak summer period is large enough to meet the peak load plus a reserve margin and any storage input requirements. Peak-load requirements in NERC region $r$ can also be met by contracting for capacity located in other NERC regions.

$RES\_MARG_{rto}$

$$
\begin{aligned}
\sum_{n}^{n\in rto} P_{rto}\cdot(1+RM_{rto}) \quad \leq \quad & \sum_{n,q}^{n\in rto} \mathrm{CONV}_{n,q} \\
+ \quad & \sum_{c,i,j}^{j\in rto} (\mathrm{WN}_{c,i,j}+\mathrm{WTN}_{c,i,j})\cdot CVmar_{c,i,rto} \\
& \qquad \cdot (1-TWLOSSnew\cdot Distance_{i,n}) \\
+ \quad & \sum_{c,i,j}^{j\in rto} (WO_{c,i,j}+WTO_{c,i,j})\cdot CVold_{c,i,rto} \\
& \qquad \cdot (1-TWLOSSold\cdot Distance_{i,n}) \\
+ \quad & \sum_{c,j,escp}^{j\in rto} \mathrm{Welec\_inregion}_{c,j,escp}\cdot CVmar_{c,i,rto} \\
+ \quad & \sum_{cCSP,i,j}^{j\in rto} (\mathrm{CspN}_{cCSP,i,j}+\mathrm{CspTN}_{cCSP,i,j})\cdot CspCVmar_{cCSP,i,rto} \\
& \qquad \cdot (1-TWLOSSnew\cdot Distance_{i,n}) \\
+ \quad & \sum_{cCSP,i,j}^{j\in rto} (CspO_{cCSP,i,j}+CspTO_{cCSP,i,j})\cdot CspCVold_{cCSP,i,rto} \\
& \qquad \cdot (1-TWLOSSold\cdot Distance_{i,n}) \\
+ \quad & \sum_{cCSP,j,escp}^{j\in rto} \mathrm{CSPelec\_inregion}_{cCSP,j,escp}\cdot CspCVmar_{cCSP,i,rto} \\
+ \quad & \sum_{n,st}^{n\in rto} \mathrm{STOR}_{n,st} + old\_STOR_{n,st} \\
+ \quad & \sum_{i,st}^{i\in n} \mathrm{WSTORout\_inregion}_{i,H16,st} + old\_WSTORout\_inregion_{i,H16,st} \\
+ \quad & \sum_{n,p}^{n\in rto} \mathrm{CONTRACTcap}_{p,n}\cdot(1-TLOSS\cdot Distance_{n,p}) \\
- \quad & \sum_{n,p}^{n\in rto} \mathrm{CONTRACTcap}_{n,p}
\end{aligned}
$$

**Operating Reserve Requirement:** Ensures that the spinning reserve, quick-start capacity, and storage capacity are adequate to meet the normal operating reserve requirement and that imposed by wind. The second and third constraints work together to ensure that no more than a set fraction (*qsfrac*) of the operating reserve requirement be met by quickstart capacity.

$OPER\_RES_{rto,m}$

$$\begin{aligned} Oper\_Res\_Reqt_{rto,m} \quad \leq \quad & \sum_{n,q}^{n \in rto} \mathrm{SR}_{n,m,q} + \mathrm{QS}_{n,q} \cdot F_q \\ + \quad & \sum_{n,st}^{n \in rto} \mathrm{STOR\_OR}_{n,m,st} + \sum_{i,st}^{i \in rto} \mathrm{WSTOR\_OR}_{i,m,st} + old\_WSTOR\_OR_{i,m,st} \end{aligned}$$

$OPER\_RES2_{m,rto}$

$$\begin{aligned} Oper\_Res\_Reqt_{rto,m} \quad = \quad & TOR_{rto,m} \\ & + \sum_{c,i,j}^{j \in rto} (\mathrm{WN}_{i,j} + \mathrm{WTN}_{i,j}) \cdot ORmar_{c,i,rto,m} \\ & + \sum_{c,j}^{j \in rto} \mathrm{Welec\_inregion}_{c,j} \cdot ORmar_{c,j,rto} \Big) \end{aligned}$$

$OPER\_RES3_{rto,m}$

$$\sum_{n,q}^{n \in rto} \mathrm{QS}_{n,q} \cdot F_q \quad \leq \quad qsfrac \cdot Oper\_Res\_Reqt_{rto,m}$$

**Spinning Reserve Constraint:** Ensures that the useful generation from a conventional plant of type *q* comprises at least a minimum fraction of the total generation in time-slice *m* in balancing authority *n*.

$SPIN\_RES\_CAP_{n,m,q}$

$$\mathrm{SR}_{n,m,q} \quad \leq \quad \mathrm{CONVgen}_{n,seasonpeak,q} \cdot FSRV_q$$

**Capacity Dispatch Constraint:** Ensures that the capacity (MW) in balancing authority *n* of type *q*—derated by the average forced outage rate for type *q* generators—is adequate to meet the load, quick-start, and spinning reserve required in time-slice *m*.

$CAP\_FO\_PO_{n,m,q}$

$$\mathrm{CONVgen}_{n,m,q} + \mathrm{SR}_{n,m,q} + \mathrm{QS}_{n,q} \quad \leq \quad \mathrm{CONV}_{n,q} \cdot (1 - FO_q)(1 - PO_{m,q})$$

**Peaking Constraint:** To prevent unrealistic cycling, base-load plants are constrained in peak time-slices to generate no more electricity than the average of that which is generated in the shoulder time-slices. Additional power is available through *CONVP*, at increased cost.

$B\_peak\_12_{n,m,q}$

$$\begin{aligned}
\text{CONVgen}_{n,H3,q\in baseload} &\leq (\text{CONVgen}_{n,H2,q\in baseload} + \text{CONVgen}_{n,H4,q\in baseload})/2 \\
\text{CONVgen}_{n,H7,q\in baseload} &\leq (\text{CONVgen}_{n,H6,q\in baseload} + \text{CONVgen}_{n,H8,q\in baseload})/2 \\
\text{CONVgen}_{n,H12,q\in baseload} &\leq (\text{CONVgen}_{n,H10,q\in baseload} + \text{CONVgen}_{n,H11,q\in baseload})/2 \\
\text{CONVgen}_{n,H15,q\in baseload} &\leq \text{CONVgen}_{n,H14,q\in baseload} \\
\text{CONVgen}_{n,H16,q\in baseload} &\leq (\text{CONVgen}_{n,H2,q\in baseload} + \text{CONVgen}_{n,H4,q\in baseload})/2
\end{aligned}$$

**Minimum Load Constraint:** To prevent baseload plants from ramping down to unrealistic levels, minimum power output can not fall below a set fraction of peak power output.

$MIN\_LOADING_{n,m,q}$

$$\text{CONVgen}_{n,m,q} + \text{CONVP}_{n,m,q} \geq \text{CONVgen}_{n,seasonpeak,q} \cdot minplantload_q$$

### A.4.5 Constraints on Storage

**Energy Balance:** Energy discharged from storage type *st* in each area *i* or *n* must not exceed the energy used to charge storage—multiplied by the round-trip efficiency for type *st* generators—within a single season.

$ENERGY\_FROM\_GRID\_STORAGE_{n,s,st}$

$$\sum_{m}^{m\in s} \text{STORout}_{n,m,st} \cdot H_m \leq \sum_{m}^{m\in s} \text{STORin}_{n,m,st} \cdot H_m \cdot STOR\_RTE_{st}$$

**Storage Dispatch Constraint:** Ensures that storage capacity of type *st*—derated by the average forced outage rate for type *st* generators—is adequate to supply all charging power, discharging power, and operating reserve demanded in each time-slice *m*.

$STORE\_FO\_PO\_GRID_{n,m,st}$

$$\text{STORout}_{n,m,st} + \text{STORin}_{n,m,st} + \text{STOR\_OR}_{n,m,st} \leq (\text{STOR}_{n,st} + old\_STOR_{n,st})(1 - FO_{st})(1 - PO_{m,st})$$

**Storage Growth Constraint:** These two constraints allocate new storage capacity (MW) to bins that have costs associated with them over and above the cost of the storage capacity itelf. The bins are defined as a fraction of the national storage capacity at the start of the period.

$STORAGE\_GROWTH\_TOT_{st}$

$$\sum_{n} \text{STOR}_{n,st} \leq \sum_{storagebp} \text{STORAGEBIN}_{st,storagebp}$$

$STORAGE\_GROWTH\_BIN_{st,storagebp}$

$$\text{STORAGEBIN}_{st,storagebp} \leq STORAGEBINCAP_{st,storagebpt} \cdot BASE\_STORAGE_{st};$$

### A.4.6 Others

**Hydropower Energy Constraint:** Restricts the energy available from hydroelectric capacity to conform to the historical availability of water.

*HYDRO_ENERGY$_n$*

$$\sum_m \mathrm{CONVgen}_{n,m,hydro} \quad \leq \quad Hen_n$$

**California Coal Restriction:** Western states can generate no more energy from coal or ogs (plants that are dirtier than gas-cc) than they can consume in-state. This is to prevent them from shipping coal-generated electricity to California.

*CALIFORNIA_COAL$_{WECCstates,m}$*

$$\sum_{dirty,n}^{n \in states} \left(\mathrm{CONVgen}_{n,m,dirty} + \mathrm{CONVP}_{n,m,dirty}\right) \quad \leq \quad \sum_{n}^{n \in states} L_{n,m}$$

**Generation from Low Sulfur Coal:** This constraint essentially adds all the coal used in the different time slices throughout the year into a single variable.

*LOWSULCOAL$_{n,q}$*

$$\mathrm{coallowsul}_{n,q \in coaltech} \quad \leq \quad \sum_m (\mathrm{CONVgen}_{n,m,q} + \mathrm{CONVP}_{n,m,q}) \cdot H_m$$

**$SO_2$ Scrubbers Constraint:** Combined capacity of the scrubbed and unscrubbed coal plants must be equal to the total of the two from the last period minus retirements. Furthermore, unscrubbed coal capacity can not exceed the unscrubbed capacity of the last period minus retirements. This allows the unscrubbed to become scrubbed, i.e., the unscrubbed capacity can decrease but the total can not. Scrubbed coal plants can be converted to cofiring via the same mechanism,

*SCRUBBER$_n$*

$$\begin{aligned} \mathrm{CONV}_{n,scr} + \mathrm{CONV}_{n,uns} + \mathrm{CONV}_{n,cofire} \quad &= \quad CONVold_{n,scr} - CONVret_{n,scr} \\ &+ \quad CONVold_{n,uns} - CONVret_{n,uns} \\ &+ \quad CONVold_{n,cofire} \\ \text{-and-} \\ \mathrm{CONV}_{n,uns} \quad &\leq \quad CONVold_{n,uns} - CONVret_{n,uns} \end{aligned}$$

*COFIRE_CAPACITY$_n$*

$$\mathrm{CONV}_{n,scr} + \mathrm{CONV}_{n,cofire} \quad \geq \quad CONVold_{n,src} - CONVret_{n,scr} + CONVold_{n,cofire}$$

**Emissions Constraint:** Ensures that the national annual emission of each pollutant ($CO_2$, $SO_2$, $NO_x$, Hg) by all generators is lower than a national cap.

*EMISSIONS*$_{pol}$

$$\begin{aligned}
\mathrm{LP}_{pol} \quad \geq \quad & \sum_{n,m,q} (\mathrm{CONVgen}_{n,m,q} + \mathrm{CONVP}_{n,m,q}) \cdot H_m \cdot CONVpol_{q,pol} \cdot CHeatrate_q \\
+ \quad & \sum_{n,m} \mathrm{STORout}_{n,m,st} \cdot STORpol_{st,pol} \cdot CHeatrate_{st} \\
- \quad & \sum_{q,n,pol}^{pol=SO_2} \mathrm{coallowsul}_{n,q} \cdot CONVpol_{q,pol} \cdot CHeatrate_q \cdot coallowsulpolred \\
- \quad & \sum_{bioclass,n} \mathrm{CofireGen}_{bioclass,n} \cdot CHeatrate_{cofire} \cdot (CONVpol_{coal,pol} - CONVpol_{biomass,pol})
\end{aligned}$$

**Geothermal Constraints:** These constraints regulate the expansion of geothermal capacity. Regional capacity is constrained by a recoverable capacity supply curve. Geothermal capacity, as shown below, is linked directly to $\mathrm{CONV}_{q,n}$ and, through it, the model's framework for dispatchable conventional technologies.

*GEOTHERMAL_GROWTH*$_n$

$$\begin{aligned}
\mathrm{CONV}_{n,geothermal} - CONVold_{n,geothermal} \quad = \quad & \sum_{geoclass} \mathrm{GeoBin}_{geoclass,n} \\
+ \quad & \sum_{egsclass} \mathrm{GeoEGSbin}_{egsclass,n}
\end{aligned}$$

*GEOTHERMAL_GROWTH_BIN*$_{geoclass,n}$

$$\mathrm{GeoBin}_{geoclass,n} + GeoOld_{geoclass,n} \quad \leq \quad GeoMax_{geoclass,n}$$

*GEOEGS_GROWTH_BIN*$_{egsclass,n}$

$$\mathrm{GeoEGSbin}_{egsclass,n} + GeoEGSOld_{egsclass,n} \quad \leq \quad GeoEGSmax_{egsclass,n}$$

**Biofuel Constraints:** These constraints regulate the capacity expansion of dedicated biomass and coal-biomass cofiring plants. Total bio-fired generation is limited by a regional feedstock supply curve. In cofired plants, biomass can contribute up to 15% of the feedstock. Biomass, like geothermal, is linked directly to the conventional variables such as $\mathrm{CONV}_{n,q}$ and $\mathrm{CONVgen}_{n,m,q}$.

*BIOPOWER_GROWTH*$_n$

$$\mathrm{CONV}_{n,biopower} - CONVold_{n,biopower} \quad = \quad \sum_{bioclass} \mathrm{BioBin}_{bioclass,n}$$

*COFIRE_GENERATION*$_n$

$$\sum_{bioclass} \mathrm{CofireGen}_{bioclass,n} \quad \leq \quad 0.15 \cdot \sum_{q,m} \mathrm{CONVgen}_{n,m,cofire}$$

*BIOPOWER_GENERATION*$_{bioclass,n}$

$$\begin{aligned}
& \mathrm{BioGeneration}_{bioclass,n} \cdot CHeatrate_{biopower} \quad + \\
& \quad \mathrm{CofireGen}_{bioclass,n} \cdot CHeatrate_{cofire} \quad \leq \quad BioSupply_{bioclass,n}
\end{aligned}$$

## A.5 Glossary of Parameters

This is a glossary of all parameters that appear in the objective function and constraints of the detailed model description.

$a_k$ The fraction of pre-2006 transmission line $k$'s capacity available to wind.

*BASE_CSP* National CSP capacity at the start of the period. (MW)

$BASE\_CSP\_inst_i$ Regional CSP capacity at the start of the period. (MW)

*BASETPCA* National transmission capacity at the start of the period. (MW)

*BASE_WIND* National wind capacity at the start of the period. (MW)

$BASE\_WIND\_inst_i$ Regional wind capacity at the start of the period. (MW)

$BioFeedstockLCOF_{bioclass,n}$ Levelized cost of feedstock at each step of the biomass supply curve.

$BioSupply_{bioclass,n}$ Amount of feedstock available at a given step on the biomass supply curve.

*CarbTax* Amount of carbon tax. (\$/ton $CO_2$)

$CCC_q$ Overnight capital cost of conventional generating capacity. (\$/MW)

$CCONV_q$ Present value of the revenue required to pay the capital cost of conventional generating capacity (\$/MW) including interest, construction, finance, and taxes.

$CCONVF_q$ Present value of the annual fixed operating costs over the evaluation period for conventional generating capacity. (\$/MW)

$CCONVV_{n,q}$ Present value over the evaluation period of the variable operating and fuel costs for generation from conventional capacity. (\$/MWh)

$CCSP_{cCSP}$ Capital cost of class *cCSP* CSP capacity. (\$/MW)

$CCt_{q,g}$ The present value of the cost of transmitting 1 MWh of power for each of E years between balancing authorities $n$ and $p$.

$CF_{c,i,m,l}$ Capacity factor by time-slice for new wind of at a class $c$, location $l$ site in supply region $i$.

$CF_{cCSP,m}$ Capacity factor by time-slice for new CSP at a class *cCSP* site.

$CFO_{c,i,m,l}$ Average capacity factor of all existing type $l$, class $c$ wind on pre-2006 lines in region $i$.

$CFO_{cCSP,m}$ Average capacity factor of all existing class *cCSP* CSP on pre-2006 lines.

$CFTO_{c,i,m,l}$ Average capacity factor of all existing type $l$, class $c$ wind on new lines in region $i$.

$CFTO_{cCSP,m}$ Average capacity factor of all existing class *cCSP* CSP on new lines.

$CG_g$ Increase in turbine price due to rapid growth in wind capacity. (\$/MW)

$CGcsp_{gCSP}$ Increase in CSP plant cost due to rapid growth in CSP capacity. (\$/MW)

$CGcspinst_{gCSPinst}$ Increase in CSP installation cost due to rapid growth in CSP capacity. (\$/MW)

$CGinst_{ginst}$ Increase in wind installation cost due to rapid growth in wind capacity. (\$/MW)

$CGStorage_{st,storagebp}$ Increase in storage cost due to rapid growth in storage capacity. (\$/MW)

$CHeatRate_q$ Heat rate (inverse efficiency) of conventional technology. (MMbtu/MWh)

$CHeatrate_{st}$ Heat rate (inverse efficiency) of storage technology. (MMbtu/MWh)

$CONVpol_{q,pol}$ Emissions of pollutant for each MWh of generation by conventional technology $q$. (ton/MWh)

$CONVold_{n,q}$ Existing conventional generating capacity, prior to the current period. (MW)

$CONVret_{n,q}$ Retirements of aging conventional capacity in a given period.

*Cost_Inst_Frac* Fraction of wind farm capital cost assigned to installation rather than the turbines themselves.

$cpop_{c,i,l}$ Fractional increase in wind capital cost due to population density.

*CQS* Cost to modify a combustion turbine to provide a quick-start capability. ($/MW)

*CRF* Capital recovery factor, i.e. the fraction of the capital cost of an investment that must be returned each year to earn a given rate of return if income taxes and financing are ignored.

$cslope_{c,i,l}$ Fractional increase in wind capital cost per degree of topographical slope.

$CSP2G_{cCSP,i,cspscp}$ New class *cCSP* CSP resource in region *i* available at interconnection cost step *cspscp*.

$CSP2GPTS_{cCSP,i,cspscp}$ Cost to build transmission from a CSP site to the closest available grid transmission capacity.

$CspCVmar_{cCSP,i,rto}$ (CSP Capacity Value - marginal) The effective load-carrying capacity of 1 MW at a new CSP plant at a class *cCSP* site in region *i* delivered to an *rto*.

$CspCVold_{cCSP,i,rto}$ (CSP Capacity Value - old) The effective load-carrying capacity of all the CSP capacity installed in previous periods whose generation is transmitted to an *rto*.

*CSPGridConCost* Cost to connect a CSP plant to the grid. ($/MW)

$CSP\_inregion\_dis_{cCSP,j,escp}$ Levelized cost—from the *escp* step of the supply curve—for building a transmission line from a CSP site to a load center in the same region.

$CSPO_{cCSP,i,j}$ Existing class *cCSP* CSP capacity on pre-2006 transmission lines from region *i* to region *j*.

$CSPOM_{cCSP}$ Present value of operations and maintenance costs over the evaluation period for CSP capacity ($/MW)

$CSPRuc_{cCSP,i}$ Amount of solar resource available. (MW)

$CSPTO_{cCSP,i,j}$ Existing class *cCSP* CSP capacity on new transmission lines from region *i* to region *j*.

$CSPTturO_{cCSP,i}$ Existing CSP capacity for which new transmission capacity was built. (MW)

$CSPturO_{cCSP,i}$ Existing CSP capacity that utilizes pre-2006 lines. (MW)

$CSRV_{n,q}$ Present value of the variable cost of spinning reserve provided over the evaluation period ($/MWh)

$CSTOR_{st}$ Capital cost of storage capacity. ($/MW)

$Ctranadder_q$ Transmission cost adder by conventional technology. ($/MW)

$CVmar_{c,i,rto}$ (Capacity Value - marginal) The effective load-carrying capacity of 1 MW at a new wind or solar farm at a class *c* site in region *i* delivered to an *rto*.

$CVold_{c,i,rto}$ (Capacity Value - old) The effective load-carrying capacity of all the wind or solar capacity installed in previous periods whose generation is transmitted to an *rto*.

$CW_c$ Present value of the revenue required to pay for the capital cost of class *c* wind capacity—including interest during construction, finance, and taxes. ($/MW)

$CWOM_c$ Present value of operations and maintenance costs over the evaluation period for wind capacity—including property taxes, insurance, and production tax credit. ($/MWh)

$Distance_{i,j}$ Distance between regions. (miles)

$Distance_{n,p}$ Distance between balancing authorities. (miles)

$F_q$ Fraction of capacity that can be available as quickstart.

$FO_q$ Forced outage rate of technology *q*.

$Fprice_{q,n}$ Cost of input fuel for given technology. ($/MWh)

$FSRV_q$ Fraction of capacity available for spinning reserve.

$FSTOR_{st}$ Present value of the annual fixed operating costs over the evaluation period for storage capacity. (\$/MW)

$GeoAdder_{geoclass,n}$ Additional capital cost for recoverable geothermal capacity along supply curve. (\$/MW)

$GeoEGSadder_{egsclass,n}$ Additional capital cost for recoverable geothermal capacity along supply curve. (\$/MW)

$GeoEGSmax_{egsclass,n}$ Amount of recoverable capacity at a given step on the EGS supply curve. (MW)

$GeoEGSOld_{egsclass,n}$ Existing EGS capacity, prior to the current period. (MW)

$GeoMax_{geoclass,n}$ Amount of recoverable capacity at a given step on the geothermal supply curve. (MW)

$GeoOld_{geoclass,n}$ Existing geothermal capacity, prior to the current period. (MW)

*GridConCost* cost to connect a wind farm or CSP plant to the grid. (\$/MW)

$Gt_g$ A fractional multiplier on the national wind capacity that defines the national wind capacity in step $g$ of the wind turbine price multiplier for rapid growth.

$GtCSP_{gCSP}$ A fractional multiplier on the national CSP capacity that defines the national CSP capacity in step *gCSP* of the CSP plant price multiplier for rapid growth.

$GtCSPinst_{gCSPinst}$ A fractional multiplier on the CSP capacity in a region that defines the region's CSP capacity in step *gCSPinst* of the CSP installation price multiplier for rapid growth.

$Gtinst_{ginst}$ A fractional multiplier on the wind capacity in a region that defines the region's wind capacity in step *ginst* of the wind installation price multiplier for rapid growth.

$H_m$ Number of hours per year in time-slice $m$.

$Hen_n$ Annual hydro energy available in balancing authority $n$. (MWh)

$L_{j,m}$ Load by region and time-slice. (MW)

$L_{n,m}$ Load by balancing authority and time-slice. (MW)

$L_{rto,m}$ Load by rto and time-slice. (MW)

$lowsuladd\_LCF_n$ Present value of 20-year expected additional levelized cost of fuel for using low sulfur coal.

$minplantload_q$ The minimum level at which a conventional technology can run.

$MW\_inregion\_dis_{c,j,escp}$ Levelized cost—from the *escp* step of the supply curve—for building a transmission line from a wind site to a load center in the same region.

$NERCRm_r$ Reserve margin requirement in the nerc region containing each balancing authority.

$nor2rto_{rto}$ The variance of the usual operating reserve requirement in RTO *rto*.

*NRRfrac* The fraction of the normal reserve requirement.

$old\_STOR_{n,st}$ Existing grid-based storage at the start of the period. (MW)

$ORMAR_{c,i,rto,m}$ The operating reserve requirement induced by the marginal addition of one MW of class $c$ wind or solar capacity in region $i$ that is consumed in an *rto*.

$P_n$ Peak load in balancing authority $n$. (MW)

$P_{rto}$ Peak load in rto *rto*. (MW)

$PcostFrac_q$ multiplier on the operating costs of conventional generating capacity for use as a peaker.

$PO_q$ planned outage rate

$PostStamp_{i,j}$ the number of balancing authorities that must be crossed to transmit wind between two supply regions.

*qsfrac* minimum fraction of operating reserve that can be met by quickstart technologies

*Resconfint* (Reserve Confindence Interval) Operating reserve minimum expressed in terms of the number of standard deviations of operating reserve required.

*RPSfraction* national renewable portfolio standard level as a fraction of national electric generation.

*RPSSCost* penalty imposed for not meeting the national RPS requirement. ($/MWh)

$St\_CSPRPSCost_{states}$ penalty imposed for not meeting the state RPS requirement for solar. ($/MWh)

$st\_Invincent_{states}$ Before-tax value of state-level investment incentive for wind. ($/MW)

$STORpol_{st,pol}$ Emissions of pollutant for each MWh of generation by storage technology *st*. (ton/MWh)

$STOR\_RTE_{st}$ round-trip efficiency for storage technologies

$st\_Prodincent_{states}$ Before-tax value of state-level production incentive for wind. ($/MW-yr)

$St\_RPSfraction_{states}$ state renewable portfolio standard level as a fraction of state electric generation.

*St_RPSSCost* penalty imposed for not meeting the state RPS requirement. ($/MWh)

$SurplusMar_{c,i,rto,m}$ Fraction of renewable (wind or solar) output (from a new class *c* source in region *i* to rto *rto*) curtailed in time slice *m* because must-run conventionals plus renewable output exceeds load.

$SurplusOld_{rto,m}$ Fraction of renewable (wind or solar) output from all existing sources feeding rto *rto* curtailed in time slice *m* because must-run conventionals plus renewable output exceeds load.

$Tk_k$ Capacity of transmission line k. (MW)

*TLOSS* Fraction of conventional power lost in each mile of transmission.

*TOCOST* cost for wind to use pre-2006 transmission lines ($/MWh-mile)

$TOR_{rto,m}$ The operating reserve requirement induced by the load, conventional generation, and existing wind capacity in an *rto*. (MW)

*TOWCOST* cost of wind transmission on pre-2006 lines ($/MWh-mile)

*TNCOST* cost of new transmission lines ($/MW-mile)

*TNWCOST* cost to build a new transmission line. ($/MW-mile)

$TPCA\_Gt_{TPCA\_g}$ A fractional multiplier of the national transmission (MW) capacity *BASETPCA* used to establish the size of growth bin *tpca_g*.

$TPCAO_{n,p}$ The transmission capacity between *n* and *p* that existed at the start of the period.

*TWLOSSnew* The fraction of wind power lost in each mile of transmission, for new wind.

*TWLOSSold* The fraction of wind power lost in each mile of transmission, for existing wind.

$VSTOR_{st}$ present value over the evaluation period of the variable operating and fuel costs for generation from storage capacity ($/MWh)

$WO_{c,i,j,l}$ Existing class *c* wind of type *l* on pre-2006 transmission lines from region *i* to region *j*.

$WR2G_{c,i,l,wscp}$ New class *c* wind resource of type *l* in region *i* available at step *wscp* on the supply curve. (MW)

$WR2GPTS_{c,i,l,wscp}$ Cost associated with step *wscp* on the supply curve to build transmission from a wind site in region *i* to the closest available grid transmission capacity. ($/MW)

$WRuc_{c,i,l}$ amount of wind resource available. (MW)

$WTO_{c,i,j}$ Existing class *c* wind on new transmission lines from region *i* to region *j*.

$WturO_{c,i,l}$ Existing wind capacity that utilizes pre-2006 lines. (MW)

$WTturO_{c,i,l}$ Existing wind capacity for which new transmission capacity was built. (MW)